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The Relationship Between Incident Wave Energy and Seacliff Erosion Rates: San Diego County, California

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ABSTRACT

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The coastline of San Diego County, California, is characterized by steep seacliffs cut into 5 to 115 m high uplifted marine terraces. Over the past few decades, rapid population growth in the area has promoted a substantial increase in cliff-top development, despite a limited understanding of the long-term cliff erosion rates and their controlling factors. Wave erosion at the base of the seacliff is usually assumed to be a basic driving mechanism of coastal cliff retreat. We investigated the influence of waves on seacliff erosion by comparing high-resolution, long-term seacliff erosion rates to wave parameters (height, energy, and power or energy flux) in 10 m of water, the break-point, and at the cliff toe. Seacliff erosion rates range from 3.0 cm/yr in well-lithified Cretaceous sandstone to 43.0 cm/yr in unlithified Pleistocene sands. The wave parameters were calculated using the California Data Information Program (CDIP) Southern California Refraction-Diffraction Model (SCRDM), an empirical relationship for breaking wave height, and a new term we define as relative power at the cliff toe. Directional wave data from offshore South-Central California were used to initialize the model. The distribution of wave power in 10 m of water and at the breakpoint and cliff toe appears to be inversely related to historical seacliff erosion rates at our study sites. As a result, our findings suggest that waves, while an important mechanism of seacliff erosion, are secondary to material properties in the overall retreat of San Diego seacliffs. Along the San Diego coastline, material strength appears to largely determine seacliff stability and the rate and manner of retreat.

ADDITIONAL INDEX WORDS: *Seacliff retreat, San Diego County, coastal hazards, wave erosion cliff materials.*

INTRODUCTION

Wave-induced seacliff erosion is a significant problem along many of the world's coastlines. Along the west coast of the United States, and in California in particular, many shoreline communities have been built on uplifted marine terraces that are threatened by long term shoreline retreat that occurs episodically during large, wave events (GRIGGS and JOHNSON, 1979; KUHN and SHEPARD, 1984; KUHN and OSBORNE, 1987; USACE, 1991; FLICK, 1994). Over the past few decades, the majority of coastal geologic, engineering, and oceanographic investigations aimed at studying the effects of wave-induced erosion have focused on beaches (NORDSTROM and INMAN, 1975; PAWKA, 1976; GABLE, 1978; HOWD and BIRKEMEIER, 1987; BIRKEMEIER *et al.,* 1989; LEE and BIRKEMEIER, 1993), unconsolidated cliffs (GELINAS and QUIGLEY, 1973; KAMPHUIS, 1987; MOON and HEALY, 1994), or scaled physical models (HORIKAWA and SUNAMURA, 1968; SANDERS, 1968; SUNAMURA and HORIKAWA, 1971; SUNAMURA, 1977, 1982, 1992) as opposed to the moderately- or well-lithified seacliffs typical of California's 1700 km coastline. The relationship between wave energy and the erosion of rocky, lithified coastlines has not been well established but is necessary if we are to understand what controls the processes of coastal erosion.

An estimated 86% of California's ocean coast is actively eroding (GRIGGS, 1992, 1995) and continued shoreline development and human occupation of potentially hazardous locations demand extensive knowledge of the mechanisms and variables which control seacliff retreat. Approximately 80% of the 32 million California residents live within 50 km of the coast and it is evident that California's coastal resources will undergo even heavier development pressure in the future (GRIGGS, 1992, 1995). While many barrier islands along the east and Gulf coasts of the United States are undergoing erosion due to Holocene sea level rise, they exist in systems characterized by unconsolidated sediment and erosion is primarily due to the lateral and shoreward migration of barrier island complexes rather than the erosion of lithified seacliffs. Erosion along California's high-energy, rocky (lithified) coastline is permanent, however, and is irreversible.

Many investigators have qualitatively documented short-term marine and terrestrial processes of seacliff retreat (SUNAMURA, 1973; KUHN and SHEPARD, 1984; GRIGGS and SAVOY, 1985; DIAS and NEAL, 1992; KOMAR and SHIH, 1993). BENUMOF and GRIGGS (1999) have established strong rela-

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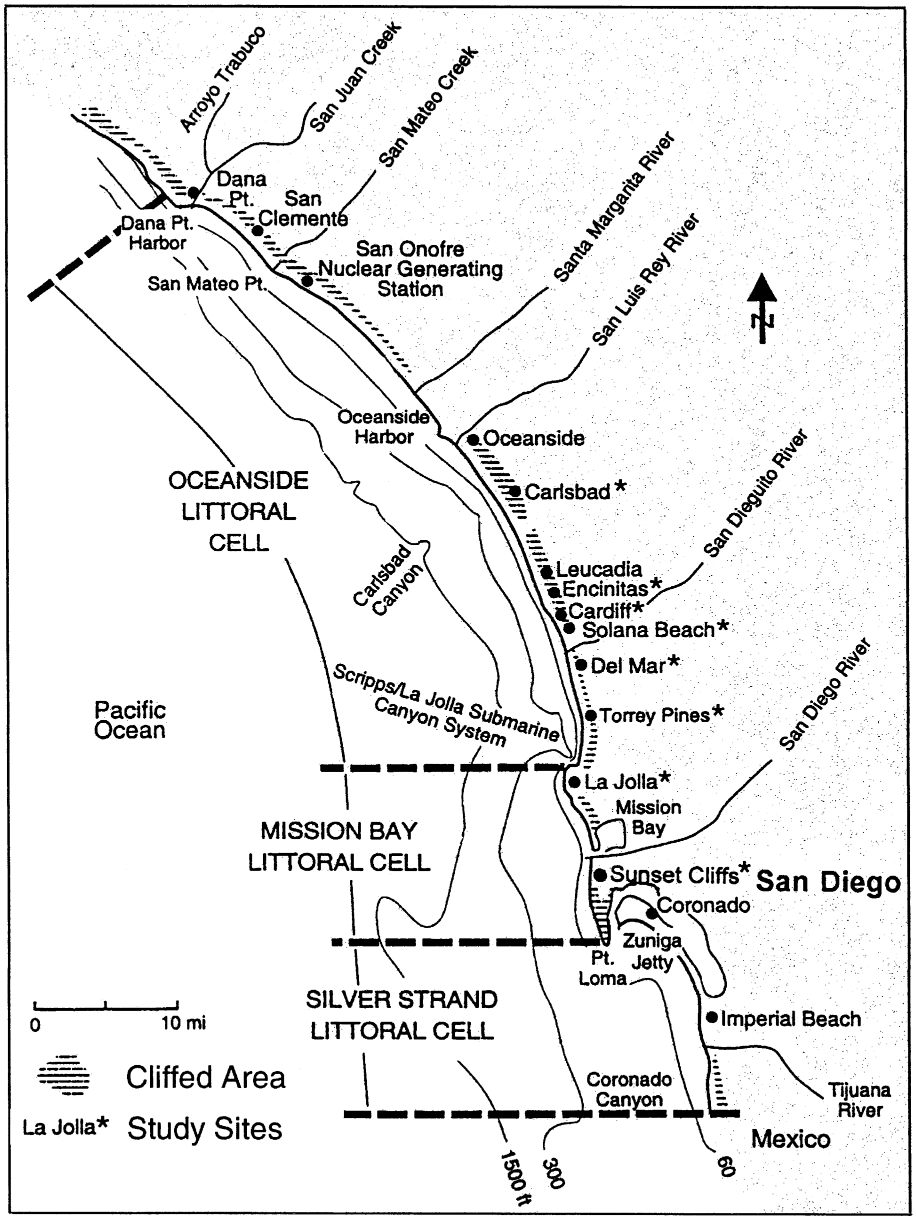


Figure 1. Map of the San Diego County coastline showing the location of major population areas and the study sites (modified from FLICK, 1994).

tionships between long-term seacliff erosion rates and the physical properties of cliff-forming materials in San Diego County, CA (Figure 1). Quantitative analyses of the influence of wave energy on seacliff erosion along rocky shorelines, however, are limited. Recently, due to the increasing use and urbanization of the coast as well as heightened public awareness of coastal erosion problems, researchers at the University of California, Santa Cruz (UCSC) Coastal Geology and Imaging Laboratory (CGIL) and University of California, San Diego (UCSD) Scripps Institution of Oceanography (SIO) have focused on quantitatively determining the relationship between wave energy and seacliff erosion rates for nine coastal cliff sites in San Diego County, California. The particular seacliffs (Figure 1), located in the coastal areas of Carlsbad, Encinitas, Cardiff, Solana Beach ('Solana'), Del Mar, Torrey Pines, La Jolla, and Sunset Cliffs ('Sunset'), vary significantly in their lithology, strength, and structure (Table 1), exposure to wave energy (Table 2), susceptibility to wave-induced erosion, and rate of erosion (Table 2; refer to BENUMOF and GRIGGS, 1999; for detailed site descriptions).

SEACLIFF EROSION AND WAVES

The basic driving mechanism of coastal cliff retreat is usually assumed to be wave erosion at the base of the seacliff

Table 1. *Generalized lithologic, strength and structural characteristics of each of the nine San Diego County seacliff sites investigated in this study.*

Parameter	CRL[1]	ENC[2]	CRDF[3]	SB[4]	DMN[5]	DMS[6]	TP[7]	LJ[8]	SSC[9]
Intact rock strength	Very Weak	Strong-Very Strong	Moderate	Strong	Very Weak	Weak	Weak-Moderate	Very Strong	Very Strong
Weathering	High	Moderate-Slight	Moderate	Moderate-Slight	High	Moderate	High	Moderate-Slight	Moderate-Slight
Spacing of joints (m)	'Infinite'	0.3–3.0	0.05–0.3	0.3–3.0	'Infinite'	0.05–0.3	0.05–0.3	0.3–3.0	0.05–0.3
Joint orientation	Extremely unfavorable, unconsolidated	Steep dips out of slope	Steep dips out of slope	Steep dips out of slope	Extremely unfavorable, unconsolidated	Steep dips out of slope	Steep dips out of slope	Steep dips out of slope	Steep dips out of slope
Width of joints (mm)	Unconsolidated	1.0–5.0	1.0–5.0	1.0–5.0	Unconsolidated	1.0–5.0	5.0–20.0	1.0–5.0	1.0–5.0
Continuity of joints	Continuous, unconsolidated	Continuous w/thin infill	Continuous w/thin infill	Continuous w/thin infill	Continuous, unconsolidated	Continuous w/thin infill	Continuous w/thin infill	Few cont./ partially cemented	Continuous w/thin-zero infill
Groundwater outflow	Slight	Slight	Moderate	Slight	Slight	Moderate-slight	Moderate	Slight-Trace	Slight

[1] CRL = Carlsbad, unlithified sand; [2] ENC = Encinitas, sandstone; [3] CRDF = Cardiff, sandy claystone; [4] SB = Solana Beach, sandstone; [5] DMN = Del Mar North, unlithified sand; [6] DMS = Del Mar South, sandy claystone; [7] TP = Torrey Pines, shale; [8] LJ = La Jolla, sandstone and shale; [9] SSC = Sunset Cliffs, sandstone and shale.

(CARTER and GUY, 1988; SUNAMURA, 1992; SHIH and KOMAR, 1994). When waves impact seacliffs they exert hydraulic forces, including compression, shear, and tension (BARNES, 1956; SUNAMURA, 1977, 1982, 1992). When sand grains or cobbles are available as abrasion and impact tools, waves may also exert mechanical action. Collectively, hydraulic and mechanical forcing may achieve quarrying of the seacliff through prying apart of jointed rocks (Figure 2) and their removal towards a free face (BAKER, 1958; EMERY and KUHN, 1980). This process, which often leads to undercutting and subsequent failure of the upper cliff, has been cited as a major cause of erosion for many San Diego seacliffs (SHEPARD and GRANT, 1947; KUHN and SHEPARD, 1984; KUHN and OSBORNE, 1987; BENUMOF and GRIGGS, 1999).

The physical properties of coastal cliffs influence erosion by either increasing or reducing the effectiveness of waves as an erosional agent. SUNAMURA (1983, 1992) divides the process of coastal erosion into two general factors under this premise: (1) the assailing force of waves upon the beach and the base of the coastal cliff, and (2) the resisting force of the beach- and cliff-forming material. The assailing force of the waves is dependent on the following parameters: (a) the water level as related to tidal variation; (b) beach sediment type and size; (c) shoreface morphology; and (d) deep-water wave characteristics. Combined,

Table 2. *Locations of wave grid cells and corresponding seacliff erosion and wave exposure data.*

Site	Location[1]	Erosion Rate[2] (cm/yr)	Stdev Erosion Rate[3] (cm/yr)	Exposure[4] (degrees)
Carlsbad	117°19′23.7818″W 33°06′07.3828″N	43.02	8.23	249
Encinitas	117°18′13.8537″W 33°03′05.9573″N	7.70	2.31	252
Cardiff	117°17′27.2443″W 33°01′22.2876″N	12.69	3.00	247
Solana	117°16′48.3801″W 32°59′25.6539″N	8.24	2.37	253
Del Mar	117°16′25.0891″W 32°57′29.0342″N	18.73 (North) 12.54 (South)	4.84	255
Torrey Pines	117°15′22.9340″W 32°53′29.2850″N	17.36	4.55	265
La Jolla	117°16′40.6347″W 32°51′06.7373″N	3.06	1.50	316
Sunset	117°15′46.2250″W 32°43′13.7348″N	7.88	3.06	260

[1] Location of wave model cell grids in 10 meters of water.
[2] Mean seacliff erosion rate.
[3] Standard deviation of seacliff erosion rates.
[4] Shore-normal coastline exposure to waves.

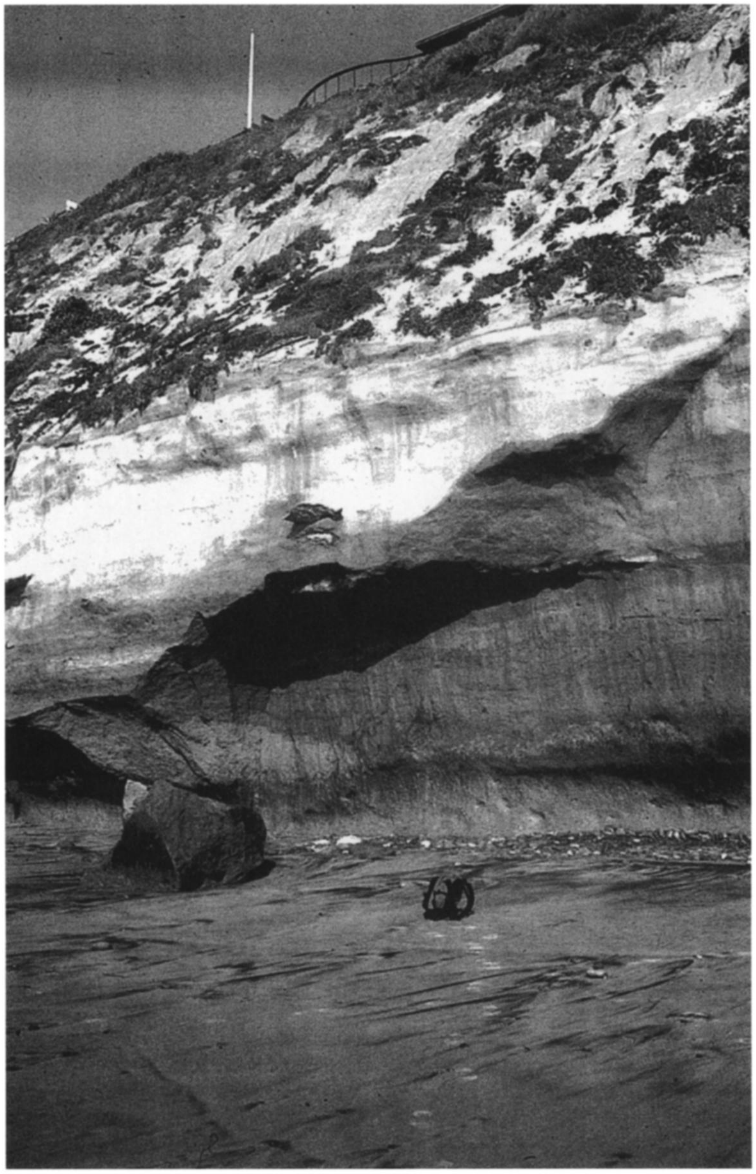


Figure 2. Block quarrying of jointed sandstone at the Solana Beach site. These cliffs are frequently attacked by waves regardless of tidal height.

these factors exert a primary control on the hydraulic force delivered to the seacliff. Due to the proximity of the study sites, however we can essentially disregard tides and deep-water wave characteristics since they are homogeneous throughout our region of study. Furthermore, beach sediment type and size, while significant along some coastlines, is not an important parameter in this investigation, for the beaches that front each of the nine studied seacliffs are significantly eroded (frequently exposing lithified bedrock) during peak winter conditions when most seacliff erosion occurs; therefore they do not provide an effective wave buffer and may be essentially disregarded (KUHN and SHEPARD, 1984; FLICK, 1994; BENUMOF and GRIGGS, 1999). The parameters which comprise the resistive force of the seacliff include: (e) lithology and stratigraphy; (f) the orientation, width, spacing, and continuity of discontinuities such as joints; (g) mechanical strength; (h) degree of biological degradation or weathering and fatigue; (j) anthropogenic effects; (k) and seismic activity. The relative intensity of the force of waves and the resisting force of the seacliff determines whether erosion occurs or does not occur (SUNAMURA, 1983, 1992). While BENUMOF and GRIGGS (1999) have established strong relationships between long-term seacliff erosion rates and important physical properties of cliff-forming materials (Table 1) such as rock strength, the geometry of structural discontinuities, groundwater seepage, and weathering, the relationship between wave forcing and seacliff erosion rates is not quantitatively well documented. The primary focus of this study is to quantify the relationship between the assailing force of waves and long-term seacliff erosion

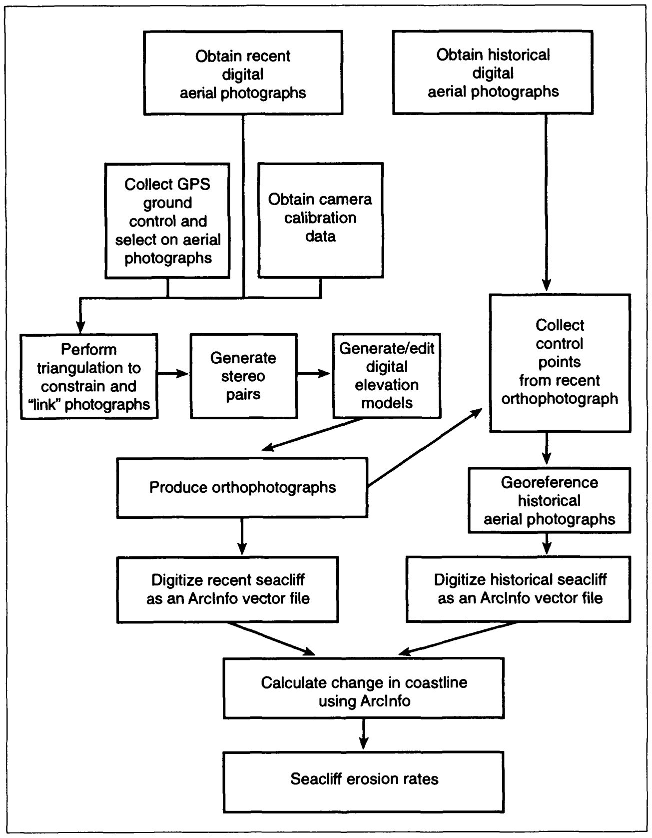


Figure 3. Generalized methodology for the determination of high-resolution seacliff erosion rates using softcopy photogrammetry, GIS, and aerial photography. The process begins with conversion of aerial photographs to orthophotographs using GPS and digital elevation models, and is completed via digitizing of the coastline using GIS and calculation of erosion rates.

rates (Table 2) in order to better understand the environmental factors controlling the natural retreat of the San Diego County coastline.

GEOLOGIC SETTING

The San Diego County coastline, from San Mateo Point in the north to the Mexican International Border, lies along the western edge of the Peninsular Range Province (WOOD and ELLIOT, 1979). Seacliffs are cut into elevated marine terraces that range from 5 to 115 meters in height and are largely composed of lithified sedimentary rocks overlain by terrace deposits. The majority of the rocks are Eocene siltstones, mudstones, shales, and sandstones capped by unconsolidated Pleistocene marine terrace deposits. Late Cretaceous sandstones, shales, and conglomerates also occur and are exposed in the seacliffs from the Point Loma Peninsula to La Jolla (KENNEDY, 1975). In general, the seacliffs composed of older Cretaceous material are more resistant to erosion than those composed of younger Eocene material, and as a result, account for the occurrence of headlands at both Point Loma and Point La Jolla.

OCEANOGRAPHIC SETTING

Wave Climate

The San Diego County wave climate is complex due to wave refraction, diffraction, and dissipation associated with offshore islands, submarine canyons, and shallow banks in the Southern California Bight (O'REILLY, 1991). The wave climate may be characterized by three dominant modes: the northern hemisphere swell, the southern hemisphere swell, and local wind-driven seas (MOFFATT and NICHOL, 1989). Northern hemisphere swells can attain deep-water wave heights exceeding 8 m and are most common in San Diego in the late fall, winter, and early spring months. Episodically, such as during the 1982–83 and 1997–98 El Niño events, winter and spring swells are displaced farther south than usual (FLICK, 1994) and many San Diego sites are more directly attacked by waves. Northern hemisphere swells are usually generated by cyclones in the north Pacific off of the Aleutian Islands but may also be produced by sub-tropical storms north of Hawaii, tropical hurricanes, and strong winds in the Eastern Pacific (FLICK, 1994). Point Conception and the offshore islands in the Southern California Bight, however, substantially block storms generated off the Aleutian Islands. The southern hemisphere swell is generated by storms and cyclones off of New Zealand, Indonesia, or Central and South America during summer months. Although southern hemisphere swells generally produce smaller waves than the northern hemisphere swell, they often have very long periods (20+ seconds) because of the intensity and persistence of storms in the vicinity of Antarctica. In general, southern hemisphere swells typically cause little to no cliff erosion along the San Diego coastline because they usually occur when beach width/height is at a maximum and are often unassociated with local energetic storm conditions (BENUMOF and GRIGGS, 1999). The local, wind-driven swells typically develop rapidly when low pressure systems track near Southern California in the winter months or when strong sea breezes are generated during the spring and summer.

Tides and Sea-level Changes

Tides and other sea-level changes greatly affect the susceptibility of any seacliff to wave-induced failure (QUIGLEY and ZEMAN, 1980; CARTER and GUY, 1988; MOSSA et al., 1992). In general, elevation of the sea surface is important because it determines the extent of cliffward wave propagation. Maximum tidal fluctuation in San Diego County is approximately 2.7 meters, however additional factors including storm surge, large-scale changes in water temperature and wind patterns, climate-related fluctuations, and long-term rise in relative sea level may contribute to increased local sea surface elevations (FLICK and CAYAN, 1985). During the winters and springs of 1982–1983 and 1997–1998, when sea-levels were unusually high due to large-scale warming of the eastern Pacific Ocean related to the El Niño-Southern Oscillation phenomenon, wave-induced beach and bluff erosion were intensified along relatively erodible sections of the coast (GRIGGS and JOHNSON, 1983; KOMAR, 1986; FLICK, 1994; FLICK, 1998; SEYMOUR, 1998; STORLAZZI and GRIGGS, 1998).

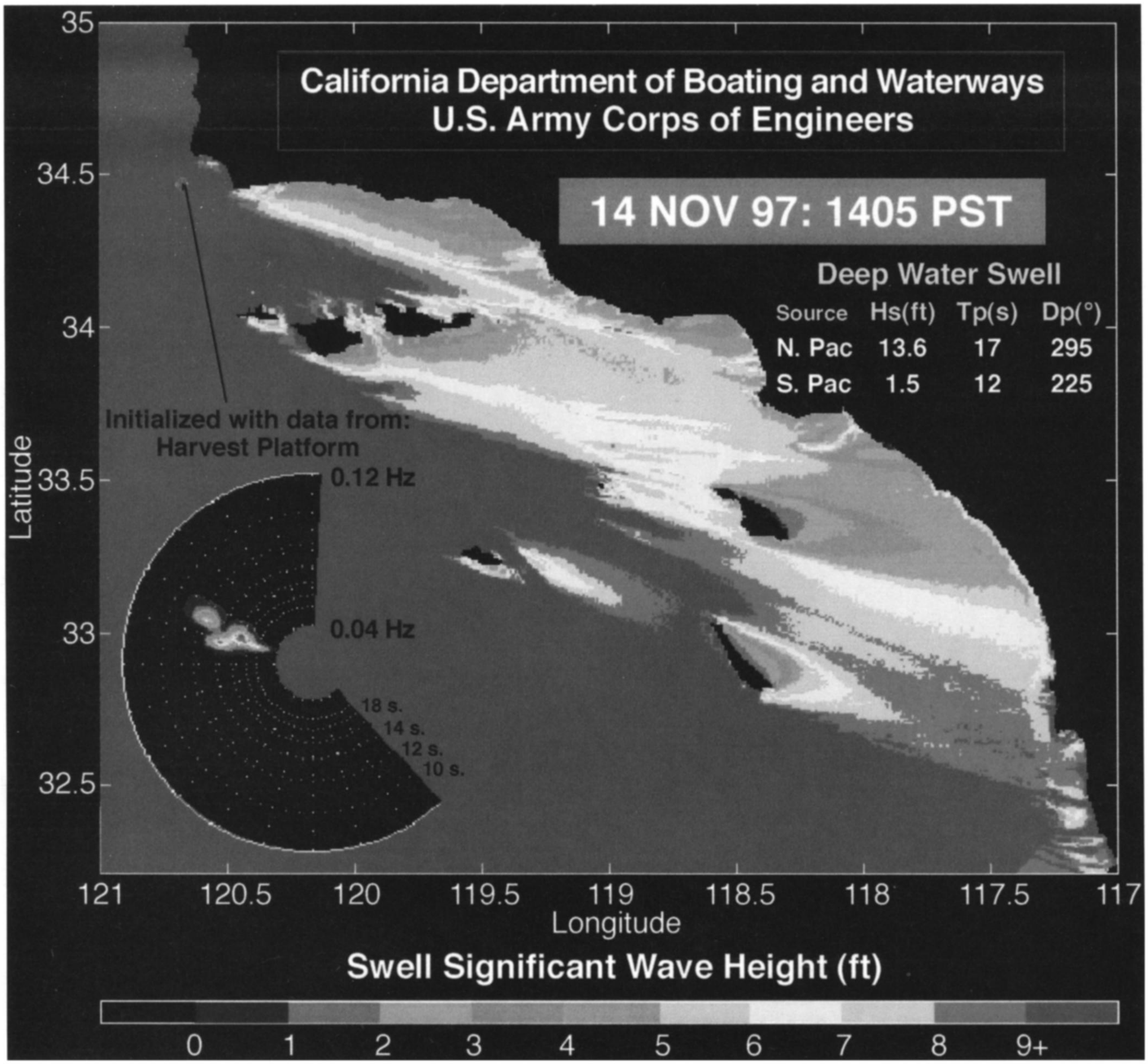


Figure 4. An example of the CDIP SRCDM wave model on November 14, 1997 showing the relative distribution of wave heights along the San Diego County coastline during a typical northwest swell. Note the lack of island sheltering along the La Jolla and Sunset Cliffs coastlines.

FLICK and BADAN-DANGON (1989) estimate that storm surge in the San Diego area, excluding the effect of waves, rarely exceeds 30 cm in amplitude; however, as shown in Table 3, during large wave events wave-induced set-up may reach heights of two meters.

Shoreface Morphology

The Southern California Bight is characterized by a narrow continental shelf and numerous offshore islands, banks, and coastal submarine canyons. The islands shelter much of the coastal mainland from the incident deep ocean wave spectra, while the banks, shelf bathymetry and coastal canyons create regions of strongly convergent and divergent wave energy (O'REILLY, 1993). As a result, wave conditions along the San Diego coastline can vary significantly over distances as short as a few kilometers.

The continental shelf along the San Diego County shoreline varies in width, from approximately 3.0 to 6.5 km along the Oceanside littoral cell, to almost 16 km at Imperial Beach (USACE, 1991). Major geomorphic features along the San Diego County regional shelf include the Carlsbad, Scripps, and La Jolla submarine canyons, which have incised as much as

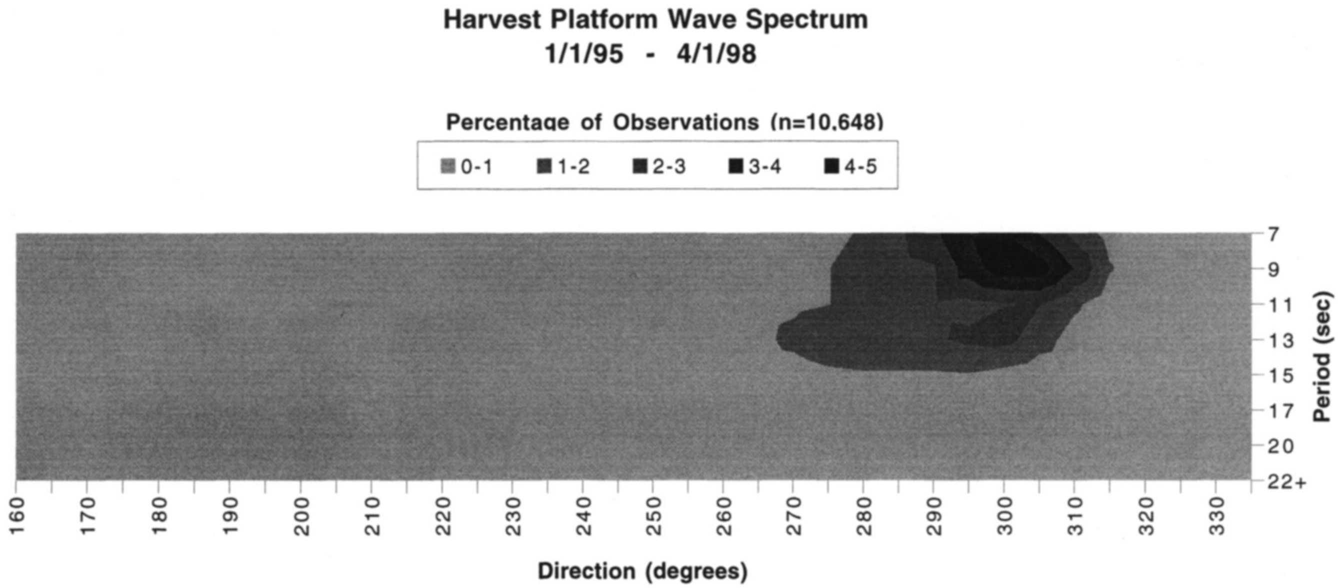


Figure 5. The Harvest Platform wave spectrum from January 1, 1995 to April 1, 1998 showing the relative percentage of observations for each direction and period used in the SCRDM model. The wave spectrum is characterized by 7–10 sec waves approaching from the northwest, particularly from the 291–309 deg range.

several hundred feet into the continental shelf (CROWELL, 1960). In addition, DARIGO and OSBORNE (1986) identified 13 smaller paleo-river channels that dissect the shelf off San Diego County. The shoreface slope from 0–20 m water depth also varies, with values ranging from approximately 0.025 at Sunset Cliffs to 0.045 at Point La Jolla.

METHODOLOGY

Seacliff Erosion Rates

Our methodology consists of comparing previously compiled high-resolution, long-term seacliff erosion rates to wave parameters in 10 meters of water and at the breaker point and cliff toe for each coastal cliff site. Long-term seacliff erosion rate data were generated for the entire San Diego County coastline, from the Mexican International border to Oceanside Harbor, as part of a nation-wide erosion hazards study funded by the Federal Emergency Management Agency (FEMA), using softcopy photogrammetry, geographic information system (GIS) technology, and recent/historical aerial photography (MOORE et al., 1999). The steps involved in the application of softcopy photogrammetry to aerial photographs are summarized in Figure 3 (for a general discussion of various photogrammetric techniques, including softcopy photogrammetry, refer to MOORE, in press). The landward-most edge of the seacliff served as the erosion reference feature for calculating erosion rates. The erosion rates employed in this study (Table 2) were determined for the period 1932 to 1994.

Wave Refraction/Diffraction/Shoaling Modeling

The wave data used in this study were obtained through the Coastal Data Information Program (CDIP), supported by the US Army Corps of Engineers and the California Department of Boating and Waterways and operated by SIO (SEYMOUR et al., 1993). Harvest Platform, operated by Chevron, and located in 225 m of water depth offshore of Point Conception in South-Central California, has hosted instruments for measuring deep water data since 1988. The Harvest Platform array includes nondirectional buoys which measure wave energy and directional buoys which measure directional properties of the wave field, to evaluate such parameters as mean wave direction and directional spread as a function of wave period. A linear, refraction-diffraction wave model (KIRBY, 1986) was used to transform the historical Harvest Platform data to wave energy estimates in approximately 10 m water depth seaward of the coastal cliff sites. The refraction-diffraction model was adapted for use in the Southern California Bight (SCRDM) by O'REILLY and GUZA (1993), and is now used routinely by the Coastal Data Information Program to provide real-time swell predictions for this region. The SCRDM (Figure 3) accounts for island blocking, refraction, diffraction and shoaling of the incident deep water waves, and has shown exceptional agreement with coastal wave measurements in field validation studies (refer to O'REILLY, 1993; O'REILLY and GUZA, 1993; and O'REILLY et al., 1993 for detailed discussion of the SCRDM).

In order to evaluate the relative influence of wave energy upon the study sites, we used directional wave data from Harvest Platform for the period from January 1st, 1995 to April 1st, 1998. This time span was selected because it included a La Nina event during the 1995–96 winter, a winter with a moderate wave climate (1996–97), and the intense El Niño-Southern Oscillation winter of 1997–98. This provided a range of wave energies and directions that is representative

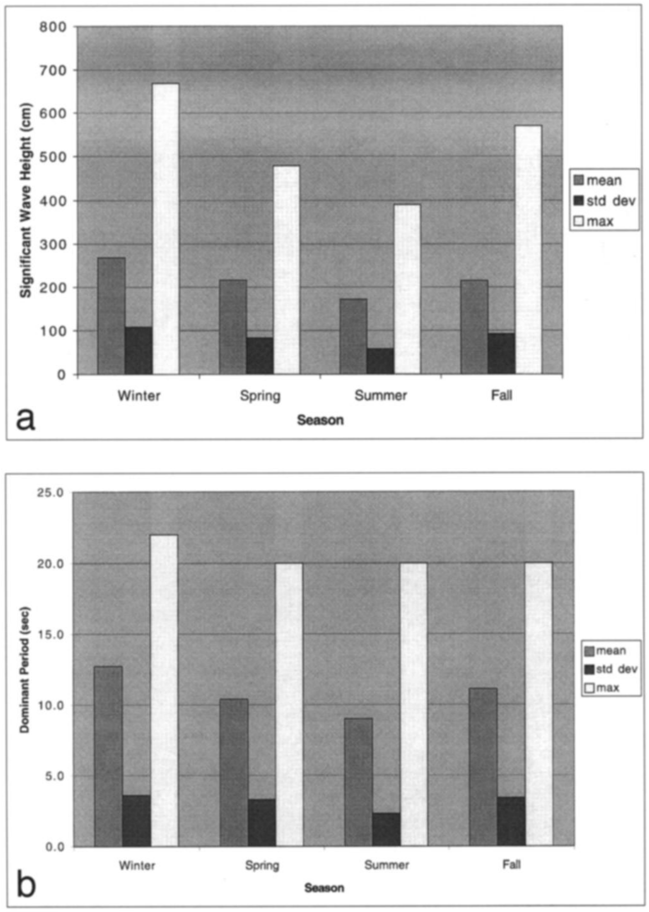


Figure 6. Harvest Platform mean, standard deviation, and maximum seasonal wave statistics for (a) significant wave height and (b) dominant period, from January 1, 1995 to April 1, 1998. During winter storms, waves can have significant wave heights in excess of 6.0 m and periods greater than 20.0 seconds.

of the San Diego County wave climate. Most importantly, though, by including the 1997–98 El Niño data, one of the largest winter events this century, and the largest in the past 25 years (SEYMOUR *et al.,* 1984; STORLAZZI and GRIGGS, 2000), is incorporated into our analyses. Furthermore, this data set provided coverage over daily and seasonal tidal fluctuations. While a total of 12,417 observations (typically 10–20 per day) were recorded at Harvest Platform between January 1, 1995 and April 1, 1998, this time period included only 10,648 observations when both energy and directional data were simultaneously recorded (Figure 5) and were thus able to be propagated shoreward by the SCRDM (Figure 4). As shown in Figure 5, the Harvest Platform wave spectrum is most characterized by 7–10 sec waves approaching from the northwest, particularly from the 291–309 deg range.

The mean wave height, period, and direction for the Harvest Platform data utilized in this study was 2.21 (0.95) m, 10.9 (3.5) sec, and 287 (26) deg, respectively with the standard deviation of each parameter in parentheses; Figures 6a and 6b show mean, standard deviation, and maximum seasonal wave statistics (significant wave height and dominant period, respectively) over the studied time period. During this time span, 4.9% of the waves observed at Harvest Platform were greater than 4 m while waves larger than 6 m were only observed 0.1% (11 observations) of the time.

Table 3. *Wave-induced total swash elevation data (KOMAR, 1998).*

Site	Mean $R^t_{2\%}$ (m)	St Dev $R^t_{2\%}$[1] (m)	Mean $R^t_{2\%}$ + 3 StDev[2] (m)
Carlsbad	0.49	0.41	1.73
Encinitas	0.59	0.49	2.07
Cardiff	0.58	0.46	1.97
Solana	0.59	0.47	2.01
Del Mar North	0.59	0.48	2.03
Del Mar South	0.54	0.44	1.87
Torrey Pines	0.56	0.45	1.91
La Jolla	0.52	0.44	1.83
Sunset	0.54	0.45	1.89

[1] Standard deviation of mean wave-induced total swash elevation (m).
[2] Mean + 3 standard deviations of mean wave-induced total swash elevation (m); this includes 99% of the total variance observed in the data set.

Table 4. *Wave model results.*

Site	H_{-10m} [1] +/− StD	H_{-10m} [2] + 3 StD	H_{bp} [3] (+/− StD)	H_{bp} [4] + 3 StD	Et_{-10m} [5] (+/− StD)	Et_{-10m} [6] + 3 StD	Et_{bp} [7] (+/− StD)	Et_{bp} [8] + 3 StD	P [9] (+/− StD)	P [10] + 3 StD	Pr_{ct} [11]
Carlsbad	1.01	3.59	1.61	5.12	46.01	342.29	8.99×10^5	9.63×10^6	2.26	18.97	13.29
	(0.86)		(1.17)		(98.76)		(2.91×10^6)		(5.57)		
Encinitas	1.06	3.70	1.67	5.33	51.68	357.83	9.91×10^5	1.08×10^7	2.60	20.48	17.19
	(0.88)		(1.22)		(102.05)		(3.27×10^6)		(5.96)		
Cardiff	0.99	3.36	1.58	4.91	45.69	327.57	7.86×10^5	7.87×10^6	2.32	18.88	15.09
	(0.79)		(1.11)		(93.96)		(2.36×10^6)		(5.52)		
Solana	1.1	3.53	1.73	5.09	52.72	338.86	9.10×10^5	7.54×10^6	2.66	19.73	16.08
	(0.81)		(1.12)		(95.38)		(2.21×10^6)		(5.69)		
Del Mar North	1.09	3.55	1.71	5.16	51.84	333.03	9.20×10^5	7.88×10^6	2.61	19.32	15.86
	(0.82)		(1.15)		(93.73)		(2.32×10^6)		(5.57)		
Del Mar South	1.09	3.55	1.71	5.16	51.84	333.03	9.20×10^5	7.88×10^6	2.61	19.32	14.62
	(0.82)		(1.15)		(93.73)		(2.32×10^6)		(5.57)		
Torrey Pines	1.18	3.76	1.82	5.42	61.17	340.89	1.01×10^6	7.49×10^6	3.09	19.77	15.32
	(0.86)		(1.20)		(93.24)		(2.16×10^6)		(5.56)		
La Jolla	1.31	4.37	1.99	6.16	76.72	464.77	1.39×10^6	1.17×10^7	3.86	27.05	20.08
	(1.02)		(1.39)		(129.35)		(3.44×10^6)		(7.73)		
Sunset	1.14	3.72	1.73	5.27	63.20	373.40	9.35×10^5	7.42×10^6	3.32	22.25	17.02
	(0.86)		(1.18)		(103.40)		(2.16×10^6)		(6.31)		

[1] Mean wave height (m) in 10 meters of water; standard deviation (m) in parentheses.
[2] Mean wave height (m) in 10 meters of water + 3 standard deviations of mean wave height (99% confidence interval).
[3] Mean wave height (m) at break-point; standard deviation (m) in parentheses.
[4] Mean wave height (m) at break-point + 3 standard deviations of mean wave height (99% confidence interval).
[5] Mean wave energy (N/m^2) in 10 meters of water; standard deviation (N/m^2) in parentheses.
[6] Mean wave energy (N/m^2) in 10 meters of water + 3 standard deviations of mean wave energy (99% confidence interval).
[7] Mean wave energy (N/m^2) at break-point; standard deviation (N/m^2) in parentheses.
[8] Mean wave energy (N/m^2) at break-point + 3 standard deviations of mean wave energy (99% confidence interval).
[9] Mean wave power (N/m-s) standard deviation (N/m−s) in parentheses
[10] Mean wave power (N/m−s) + 3 standard deviations of mean wave power (99% confidence interval).
[11] Relative power at cliff toe; (mean P + 3StDev of mean P) * [(mean $R^t_{2\%}$ + 3StDev of $R^t_{2\%}$)/max $R^t_{2\%}$]; $R^t_{2\%}$ is wave-induced total swash elevation as derived by KOMAR (1998).

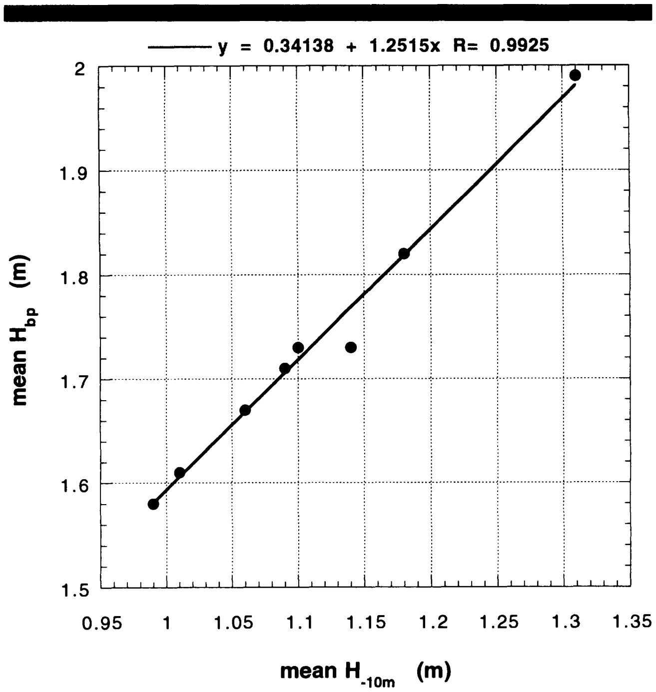


Figure 7. The relationship between mean wave heights in 10 m of water and at the break-point for each coastal cliff site.

The SCRDM refraction grids for each site were applied to the Harvest Platform wave data to obtain the wave heights in 10 m of water off each of the cliff sites, corrected for changes in energy due to refraction, diffraction, and shoaling. The total energy and power or energy flux for each observation in 10 m of water was calculated using the corrected wave heights and by solving the linear-Airy wave equation iteratively for the local wavelength. Since we lacked modern, high-resolution bathymetry (*e.g.*, multibeam sonar or LIDAR) for each of the study sites, we utilized shoreface bathymetry (2.0 m contour interval) generated by SIO and the empirical relationship for breaking wave height as a function of wave height and period derived by KOMAR and GAUGHAN (1972). Since we were concerned with the relative amount of wave energy or power between sites, the empirical relationship for breaking wave height derived by KOMAR and GAUGHAN (1972) was deemed suitable. Furthermore, the KOMAR and GAUGHAN (1972) equation has been successfully tested in the field along the SIO coastline as well as along the east coast of the United States and in the laboratory. Wave energy and power at the break-point were derived from the breaking wave heights using linear-Airy wave theory. Total swash elevation data (Table 3), which accounts for the slope of the shoreface and wave parameters, was calculated based on an equation derived by KOMAR (1998).

RESULTS

The distribution of wave height, energy, and power at each seacliff site in 10 m of water, at the break-point, and at the cliff toe is shown in Table 4. Calculations of breaking wave height using the KOMAR and GAUGHAN (1972) equation vary uniformly along the coastline with the 10 m wave heights determined using the SCRDM (Figure 7). This correlation between wave height in 10 m of water and at the break-point is statistically significant at the 0.1% level.

An increasing trend in mean wave height, energy, and power exists from Carlsbad south to La Jolla (Figure 8). Mean wave heights in 10 m of water range from 0.99 m at Cardiff to 1.31 m at La Jolla, while mean wave heights at the breaker-point vary similarly, ranging from 1.58 m to 1.99 m, respectively. Since wave energy and power are a function of the wave height squared, patterns in the distribution of wave energy and power, in both 10 m of water and at the break-point, are similar. Much of this southward increasing trend is a result of the northern San Diego coast being sheltered by offshore islands in the Southern California Bight (Figure 4). During northwesterly swells, waves have greater height (and therefore greater energy and power) at the La Jolla and Sunset sites because of a general lack of sheltering. The values for energy at the break-point are orders of magnitude higher than in 10 m of water due to their dependence on the inverse of wavelength which substantially shortens in shallow water due to shoaling.

Table 5 displays the number and percentage of observations recorded in 10 m of water as compared to Harvest Platform, as well as the number and percentage of observations greater than 4 and 6 meters at each site in both 10 m of water and at the break-point. With the exception of the Encinitas site, approximately twice as many wave observations in excess of 4 and 6 meters were recorded at the La Jolla site compared to the northern San Diego County sites. In addition, there were approximately four times as many observations greater than 4 and 6 m at the break-point as compared to 10 m of water.

In order to understand the influence of wave parameters on seacliffs, we are primarily interested in the forces imposed on the toe of the seacliff. Since we lack quantitative data on these forces, we defined a relative wave power at the cliff toe (Pr_{ct}) to describe the influence of the interaction between wave power; wave-induced set-up, and wave run-up:

$$Pr_{ct} = P\{R^T_{2\%}\}/\max(R^T_{2\%})$$

Where: $P = ECn$ and $R^T_{2\%}$ is the total swash elevation (sum of the wave induced set-up, η_{max}, and the 2% exceedence run-up elevation, $R_{2\%}$) as defined by KOMAR (1998). This variable, by including a standardized total swash elevation, is a function of the shoreface slope and therefore takes into account the variation in width of the surfzones between the sites and is collaborated by qualitative observations. By incorporating the surfzone width, energy dissipation between the break-point and shoreline, which is a function of surfzone width and is key to understanding the delivery of energy to the seacliff, is addressed. Thus, the relative wave power at the cliff toe increases with increasing relative total swash elevation as less energy is dissipated across the surfzone and more water interacts with the cliff face. As demonstrated in Figure 9d, the relative wave power at the cliff toe is inversely proportional to the previously determined seacliff erosion rates for our study sites; this relationship is shown to be statistically

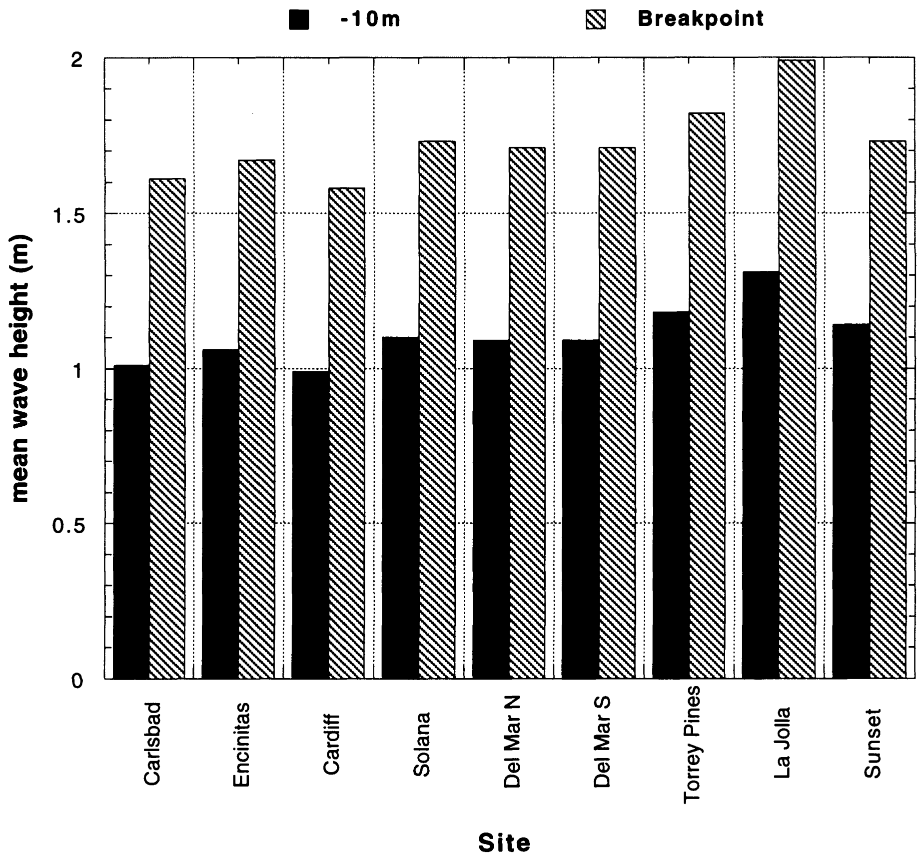


Figure 8. Alongshore variation in mean wave height in −10 m of water and at the break-point wave. Note the increasing trend in mean wave height from Carlsbad south to La Jolla (where wave energy is focused by resistant rocks).

significant at the 1.0% significance level. These differences in relative wave power at the cliff toe are supported by numerous field observations over varying seasons and oceanographic conditions (BENUMOF and GRIGGS, 1999).

DISCUSSION

Many investigators have discussed the significance of waves in the erosion of seacliffs and we concur that waves are an important mechanism of coastal cliff erosion and bluff retreat. Waves do attack seacliffs, exerting significant hydraulic and mechanical force, and are necessary for removing talus material deposited at the base of seacliffs by subaerial erosion. At the Encinitas, Solana, La Jolla, and Sunset sites, wave attack occurs frequently throughout the year due to the lack of an ample protective beach. At the Carlsbad, Cardiff, Del Mar, and Torrey Pines sites, direct wave attack during the summer and late fall is less frequent due to a relatively wide beach, but regularly occurs during large winter and spring wave events (especially during high tides). Our findings suggest, however, that wave parameters, along the San Diego coast, are secondary to lithology and material strength in explaining the variability in rate of erosion and overall retreat of seacliffs. As displayed by the relationships between seacliff erosion rates and (1) wave power; (2) wave energy in 10 m of water; (3) wave energy at the break-point; and (4) relative wave power at the cliff toe (Figures 9a, 9b, 9c, and 9d; respectively), the distribution of power (energy flux) and energy appears to be inversely related to historical seacliff erosion rates at our study sites.

While the relationship between wave power/energy and seacliff erosion rates may initially seem counter-intuitive, it in fact, supports the predominant theory regarding the evolution of seacliffs. These findings provide quantitative evidence supporting the long-standing concept that resistant rocks form coastal projections or headlands which focus wave energy or power (BASCOM, 1980; RITTER, 1986). In addition, our results support the findings of BENUMOF and GRIGGS (1999) who established strong relationships (statistically significant at the 1.0% level) suggesting that the rate of seacliff erosion in San Diego County to is linked to lithology, material strength, and geologic structure. While BENUMOF and GRIGGS (1999) documented waves as an important *mechanism* of coastal cliff erosion at many locations, their results suggest the primary *control on the rate* of seacliff retreat in San Diego is the nature of the seacliff material itself.

Furthermore, monitoring of our nine coastal cliff sites (from 1995–present) under a variety of wave conditions has provided qualitative documentation for the aforementioned

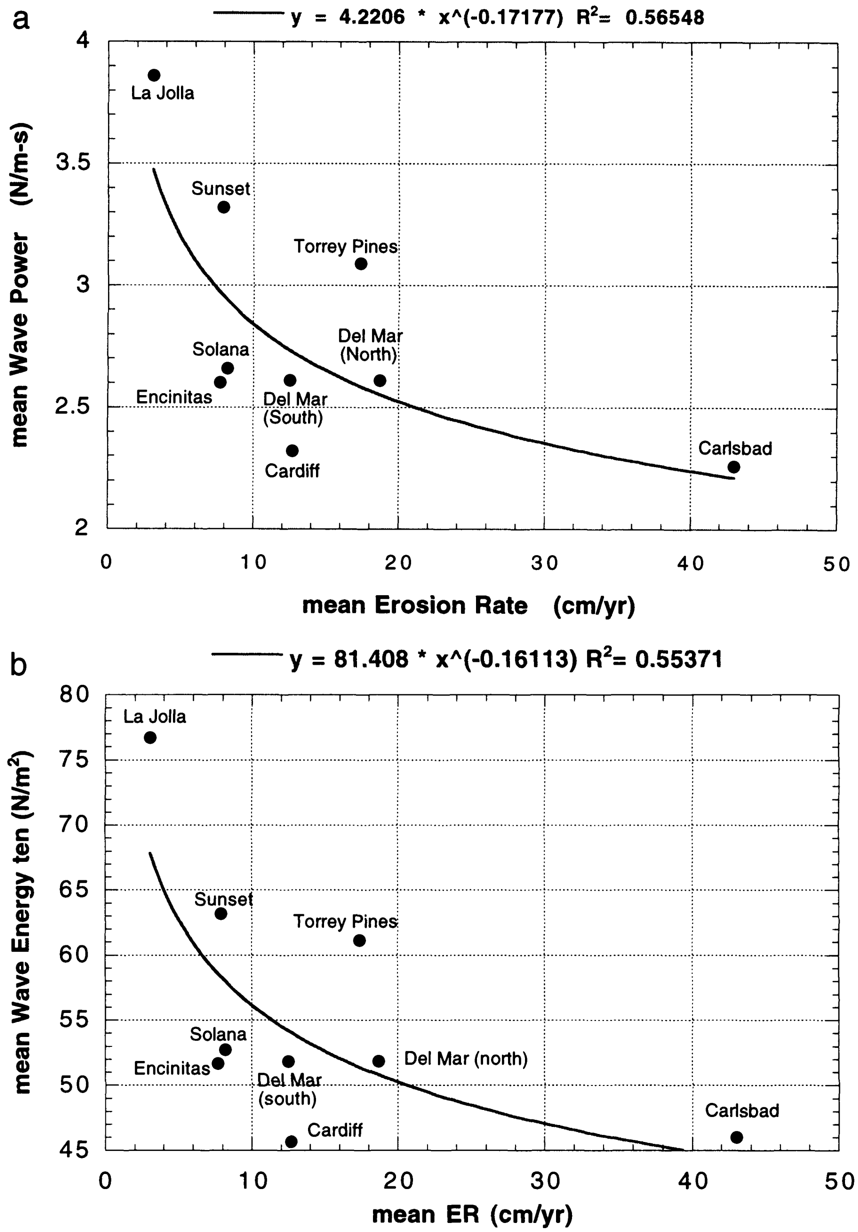
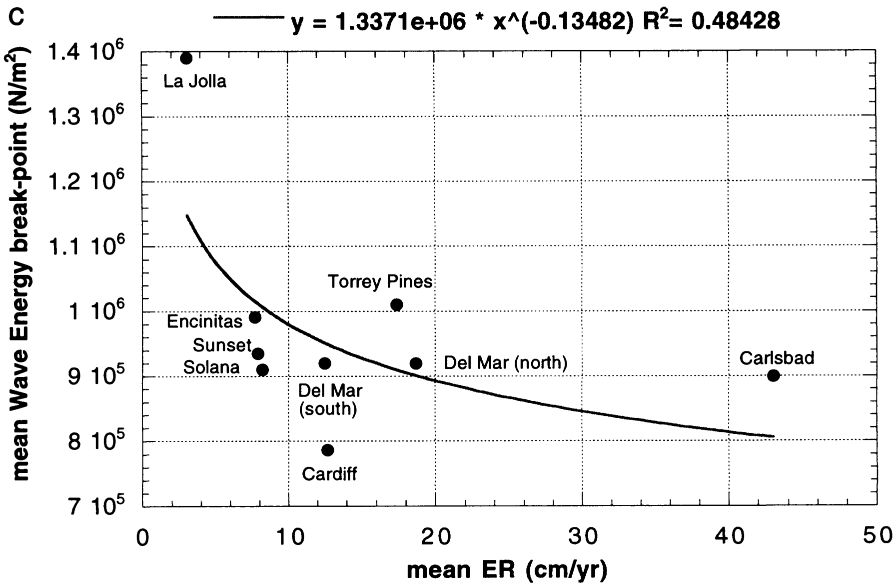


Figure 9. The relationship between seacliff erosion rates and (a) mean wave power, (b) mean wave energy in 10 m of water, (c) mean wave energy at the break-point, and (d) relative wave power at the cliff toe. These results suggest that the material comprising seacliffs is the dominant influence on seacliff erosion rates and the resulting landforms produced.

inverse relationship at the cliff face. For example, there is great variation in magnitude of high tide wave impact between the more-erodible sites (Carlsbad, Cardiff, Del Mar, and Torrey Pines) and the more-resistant sites (Encinitas, Solana Beach, La Jolla, and Sunset Cliffs). Similarly, there is great variation in low-tide wave run-up between these sites. In general, wave energy reaching the cliff base at the Carlsbad, Cardiff, Del Mar, and Torrey Pines sites is relatively insignificant at high tide and almost always nonexistent at medium to low tide. In fact, over the course of the 1997–1998 El Niño event, which included the 3–6 m swells of late January and February at 2.0–2.1 m high tides, marine-driven cliff failure was absent at the Carlsbad site except in isolated locations. At the Carlsbad site, the only areas where waves eroded the cliff were where "point-source" spring sapping (at the beach level) exacerbated the lowering and removal of the back-beach berm, so that wave run-up caused localized saturation and scour and removal of basal material. In contrast, waves reaching the cliff base at the Encinitas, Solana Beach, La Jolla, and Sunset Cliffs sites



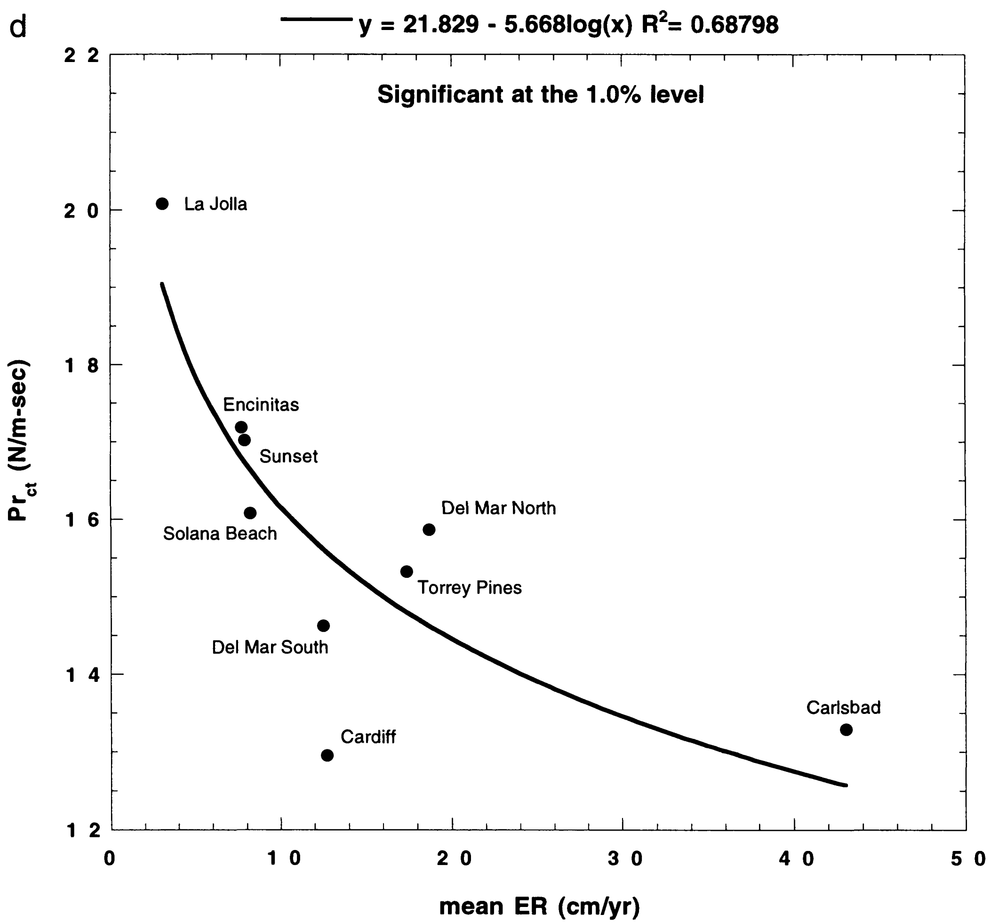


Figure 9. Continued.

Figure 10. The La Jolla site on January 30, 1998 showing wave hammering of the cliff face at high tide. These cliffs have remained essentially stable over much of this century despite being frequently attacked by large waves that break relatively close to the cliffs.

during these same events were extremely powerful, often "shaking" and "rattling" the cliff (Figure 10). In fact, condominium residents in Solana Beach experienced "the shaking of condominium walls at regularly-spaced intervals," on many occasions (ASHER, 1998). Furthermore, wave attack at the Encinitas, Solana Beach, La Jolla, and Sunset Cliffs sites is not limited to high tides; the negative low tide wave run-up is often within 5–10 meters of the cliff base (Figure 11).

CONCLUSIONS

Although the natural process of seacliff erosion is complex and is the cumulative result of numerous interacting variables that are significant at various spatial and temporal scales, wave erosion at the base of the seacliff is usually assumed to be the basic controlling factor on the process of coastal cliff retreat. However, quantitative analyses of the relationship between wave energy and the erosion of rocky, lithified coastlines have not been well established, and are necessary if we are to understand what controls the process of coastal erosion.

We investigated the influence of waves on seacliff erosion along the San Diego County, California coastline by comparing high-resolution, long-term seacliff erosion rates to wave parameters (height, energy, and power or energy flux) in 10 m of water, at the break-point, and at the cliff toe. The studied seacliffs, located in the coastal areas of Carlsbad, Encintias, Cardiff, Solana Beach, Del Mar, Torrey Pines, La Jolla, and Sunset Cliffs, very significantly in their lithology, strength, and structure, exposure to wave energy, and rate of erosion. Our findings reveal that the distribution of wave power in 10 m of water and at the breakpoint and cliff toe is inversely related to historical seacliff erosion rates at our study sites.

Although it is often difficult to separate the importance of marine and terrestrial mechanisms from lithologic variables in the erosion of coastal cliffs, our findings, combined with the findings of BENUMOF and GRIGGS (1999), suggest that the material comprising seacliffs is the dominant influence on seacliff erosion rates and the resulting landforms produced. In a real sense, the collective findings suggest that while waves are a primary control on the *timing* of seacliff erosion, material strength largely determines whether seacliffs will be stable or, if they retreat, the *rate* and *manner* of their erosion.

Our future efforts will be concentrated on gaining an even more comprehensive understanding of cliffed or rocky coastline evolution with the objective of studying the seacliff erosion process in its entirety. By studying the interaction among both the intrinsic and extrinsic controlling factors involved in seacliff erosion (most likely through rigorous multivariate analysis), whose relative importance can vary over a range of temporal and spatial scales, we aim to develop a conceptual model that will explain the evolution of coastal cliff erosion in San Diego County over both short (decadal) and longer time-scales.

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Figure 11. The Solana Beach site showing the landward extent of the low tide (0.3 m) wave (1–2 m) run-up. Wave-induced erosion of these cliffs is not limited to high tides.

Table 5. *Wave observation data in 10 m of water and at the break-point.*

Site	−10 m/Harvest[1]	−10 m (>4 m)[2]	−10 m (>6 m)[2]	Break-point (>4 m)[3]	Break-point (>6 m)[3]
Carlsbad	7109/10648 (66.76%)	83 (1.17%)	19 (0.27%)	301 (4.23%)	63 (0.89%)
Encinitas	7717/10648 (72.47%)	111 (1.44%)	30 (0.39%)	340 (4.41%)	90 (1.17%)
Cardiff	8086/10648 (75.94%)	66 (0.82%)	7 (0.09%)	262 (3.24%)	53 (0.62%)
Solana	7719/10648 (72.49%)	66 (0.86%)	6 (0.08%)	299 (3.87%)	55 (0.71%)
Del Mar[4]	8088/10648 (77.62%)	83 (1.03%)	10 (0.12%)	333 (4.12%)	63 (0.78%)
Torrey Pines	8220/10648 (77.20%)	76 (0.92%)	0 (0.00%)	451 (5.49%)	49 (0.60%)
La Jolla	8265/10648 (77.62%)	196 (2.37%)	19 (0.23%)	666 (8.06%)	149 (1.80%)
Sunset	10192/10648 (95.72%)	81 (0.79%)	11 (0.11%)	460 (4.51%)	63 (0.62%)

[1] Ratio of wave observations (percentage of observations) in 10 m of water as compared to Harvest Platform.
[2] Number of observations (percentage of observations) in 10 m of water with wave heights greater than 4 and 6 meters, respectively.
[3] Number of observations (percentage of observations) at break-point with wave heights greater than 4 and 6 meters, respectively.
[4] Del Mar North and Del Mar South.

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